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SIMULATION OF RADIO WAVE PROPAGATION IN ARCHED CROSS-SECTION TUNNELS

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ABSTRACT

Since several years, wireless communication systems are developed for train to infrastructure communication needs related to railway or mass transit applications. The systems should be able to operate in specific environments like tunnels. In this context, specific radio planning tools have to be developed to optimise system deployment. Realistic tunnels geometries are generally of rectangular cross-section or arched shape. Furthermore, they are mostly curved. In order to calculate electromagnetic wave propagation in such tunnels, specific models have to be developed. Several works dealt with retransmission of GSM or UMTS [1], [2]. Few theoretical or experimental works focused on 2.4 GHz or 5.8 GHz bands. In this paper, we will propose an approach to model radio wave propagation in these frequency bands in arched shape cross-section straight tunnels using tessellation in multi-facets. The model will be based on a Ray-Tracing tool using images method. Work reported in this paper will also show the propagation loss variations according to the shape of tunnels. A parametric study on the size of facets to model the cross-section will be realized. Finally, the influence of some parameters like the dimensions of tunnels and the frequency of signals will be examined.

1. INTRODUCTION

Wireless communication systems are more and more developed in the transportation field for train to ground or train to train communications in the railway or mass transit domains. These systems are developed to satisfy control-command needs and also high data rate transmissions for multi-media or other operational applications. Several existing systems already deployed in the world lean on IEEE802.11x standards. They work in 2.4 GHz or 5.8 GHz bands. The prediction of radio coverage levels is required to optimize deployment phases and ensure available and robust links. Generally, minimal field levels are required to guaranty key performance indicators related to safety constraints. In tunnels, usual laws of free space propagation are no more valid and propagation in tunnels has to be specifically analyzed to ensure radio coverage. The case of tunnels areas is generally treated via intensive measurements campaigns requiring time and money. The development of a specific simulation tool is then very relevant.

The paper focuses on obtained results at 2.4 GHz and 5.8 GHz bands in arched shape cross-section straight tunnels. A method of tessellation in multi-facets of the cross-section is used. The model is based on a Ray-Tracing tool using images method.

First part of the paper is dedicated to the evaluation of different models that can be used to characterize radio wave propagation in tunnels. The second part details method of tessellation. Particularly, obtained results in arched shape cross-section straight tunnels at 1 GHz are presented. The influence of shape of tunnels is highlighted and a parametric study on the number of facets to model the cross-section is realized. The third part of the paper is devoted to the study of the influence of dimensions of tunnels and frequency of signals, focusing on 2.4 GHz and 5.8 GHz bands. Finally, conclusions and perspectives of the work are given.

2. EVALUATION OF MODELS FOR RADIO WAVE PROPAGATION IN TUNNELS

In order to characterize the radio wave propagation in tunnels, several modelling approaches can be evaluated. The numerical resolution of Maxwell's equations would be an ideal solution. However, this kind of techniques is not feasible due to the enormous computational burden. A more conventional way to solve the problem is given by modal theory. The tunnel is here treated as a hollow waveguide with dielectric boundaries. Unfortunately, analytical expressions of the different constants, such as cut-off frequency and wave impedance, only exist for few canonical types of configuration, e.g. rectangular or circular cross-section waveguides [3]. A means to predict wave propagation with an adequate accuracy in finite time is given by ray optics solutions. These solutions can be adopted in tunnels because dimensions of objects in tunnel are large compared to the considered wavelength (frequency above 1 GHz). Several methods based on ray-optical modelling approach have been proposed to model wave propagation in tunnels. They used ray launching [2], [4], images method [5] or combination of both [1]. They have all in common that they can only treat the case of straight and rectangular tunnels. Classical approach of Ray-Tracing techniques cannot be transposed to the case of curved surfaces. Indeed, images method is not applicable because of the infinite line of images of one source compared to a lonely point for plane surface. For the ray launching, the concept of reception sphere is no more valid for curved surfaces because of the non-conservation of reflection angles [6]. The first conceivable solution to treat the propagation in environments where curved surfaces are present is the development of a completely novel model based on ray optics like in [6]. The second option for non-rectangular cross-section straight tunnels is to consider the equivalent rectangular cross-section tunnel with equal area. The last solution is to tessellate geometries into multiple planar facets [1], [5], [7].

3. SIMULATION RESULTS – INFLUENCE OF NUMBER OF FACETS

A Ray-Tracing method [9] combined to a tessellation of the curvature of the tunnel will be used. In a first part, the simulation tool is presented as well as the tessellation principle. Then, simulation configurations are detailed. Finally, a parametric study on the size of facets is realized to model the arched section.

3.1. Method of tessellation

The Ray-Tracing method consists in a direct research of geometric paths leading by the waves. It allows determining exactly the set of paths from a transmitter to a receiver. This technique is based on the images theory, that leans on Snell-Descartes formulas. From these paths, the Electric field is computed from Geometrical Optic (GO) laws and from Fresnel coefficients. In the case of a curved surface, one source generates an infinite number of images. To solve this problem, we choose to approximate the curved surface by facets. Several problems appear such as the position of the facets and the optimal size of facets. In [7], a first approach of tessellation of a curved surface is presented in the case of a 2D curvature. A method developed in [1] uses triangular facets to model the curved surface. An hybrid method based on a Shooting and Bouncing Ray (SBR) combined to the images theory is tested in some particular configurations of tunnels. Finally in [5], a tool developed for planning and design of wireless systems is presented. It is based on Ray-Tracing techniques. Similar results to Cheng & Jeng [1] are obtained.

The use of the tessellation raises the problem of the size of facets to be used to represent a given curvature. A compromise has to be found on the number of facets retained. It has to be sufficient to represent the geometry of the arched section but not too large to stay in the limit of validity of the physical model based on a high frequency approach.

3.2. Configurations of simulations at 1 GHz

Three configurations of simulations of straight tunnels with equivalent cross-section area from Cheng & Jeng [1] are considered, illustrated on Figure 3.1 : the tunnel A is a rectangular cross-section tunnel, the tunnel B represents the intermediate tunnel, an arched cross-section tunnel modeled with 3 facets, and the tunnel C is an arched cross-section tunnel modeled with *n* facets. A 1 GHz frequency is considered. The transmitting and receiving antennas are dipoles vertically polarized and placed respectively in (4, 0, 4.5) and (2.1, y, 1.5), where y represents the longitudinal direction of tunnel and varies from 10 to 150 m with a step of 1 m. Results for tunnels A and B are rapidly obtained. For the tunnel C, a study on the number of facets characterizing the arched section has to be realized. To have a valid physical model, the high frequency approach involves a size of facets $d >> \lambda$, with λ the wavelength. We assume that these conditions are respected for $d > 2\lambda$. Given the tunnel dimensions, the condition on the number of facets n is as follows :

$$4 \leq n \leq 20 \qquad (1)$$

3.3. Simulation Results

All results are given in term of signal attenuation (in dB) function of the distance between transmitter and receiver. Only the phenomenon of reflection is considered in the simulations. Indeed, it represents the dominant effect in empty tunnel : there is no transmission because of the tunnel walls properties and no diffraction because of the lack of edge.

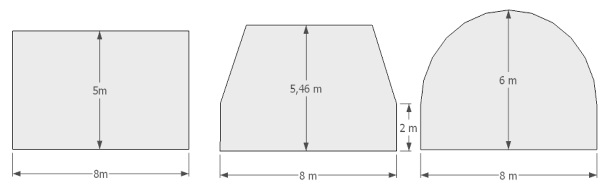

Figure 3.1 : Geometry of tunnels

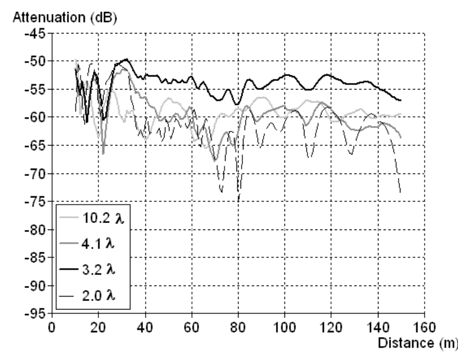

Figure 3.2 : Results for Tunnel C function of facets size

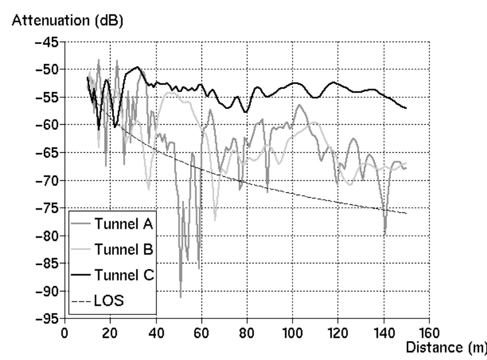

Figure 3.3 : Results for Tunnels A, B, C
facets size : 3.2λ

Figure 3.2 presents results obtained for tunnel C function of the size of facets. An important variation of signal level can be observed from a configuration to another. Results obtained in simulations are compared to results from [1] considering an arched section represented by facets with a size of 3.2λ, which gives the higher signal level. It is important to note that the higher level does not inevitably correspond to the real level. We will see later that one of the perspectives of the work will be to compare with some measurements in realistic tunnels. Figure 3.3 shows the obtained results for the tunnels A, B and C and highlights a concordance with results of [1]. A « focusing » effect in term of signal level is observed for the arched section compared to the rectangular section. This phenomenon is characterized by smaller depth fadings and a higher global signal level. The signal level is also compared to the free space case in Line Of Sight (LOS).

4. FREQUENCY AND TUNNEL DIMENSIONS INFLUENCE

4.1. Frequency influence

In this part, the frequency is varying for a similar geometry of tunnels. High frequency conditions have to be respected. At 2.4 GHz, equation (1) becomes :

$$4 \leq n \leq 50 \qquad (2)$$

and at 5.8 GHz, this condition becomes :

$$4 \leq n \leq 120 \qquad (3)$$

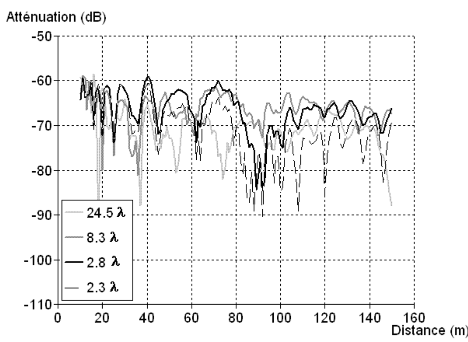

Figure 4.1 : Results for Tunnel C vs. facets size 2.4 GHz

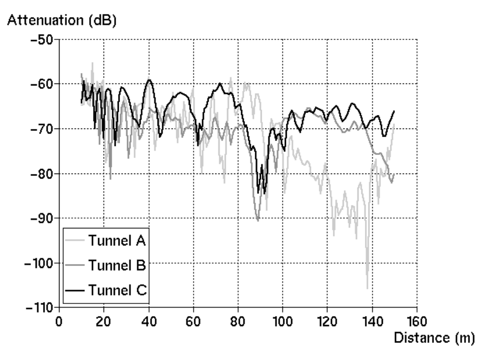

Figure 4.2 : Results for Tunnels A, B, C (facets size = 2.8λ) - 2.4 GHz

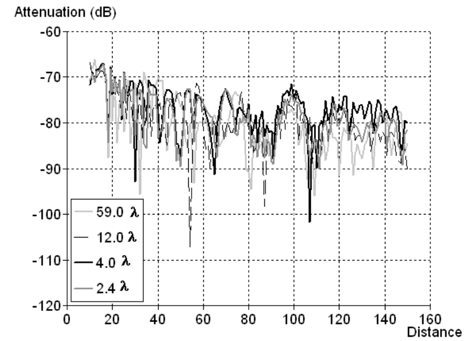

Figure 4.3 : Results for Tunnel C vs. facets size 5.8 GHz

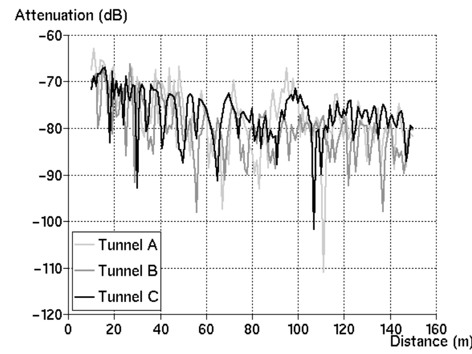

Figure 4.4 : Results for Tunnels A, B, C - facets size : 4λ - 5.8 GHz

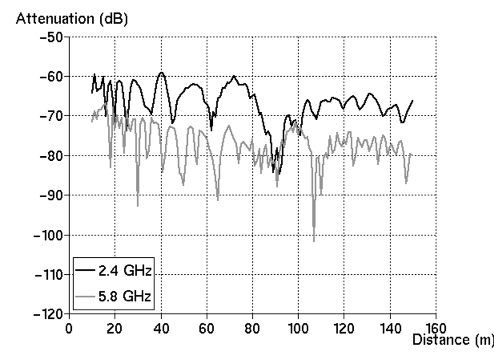

Figure 4.5 : Results for Tunnels C 2.4 GHz - 5.8 GHz

Figures 4.1 and 4.3 illustrate simulation results for the 2 frequencies. Some significant variations can also be observed from a result to another. Figures 4.2 and 4.4 illustrate results obtained at 2.4 GHz and 5.8 GHz for the 3 tunnels A, B, C. A size of facets giving the higher signal level is also considered.

Figure 4.5 illustrates the results of tunnel C, with a size of facets giving the higher level, for the 3 frequencies to highlight the effect of frequency on signal level.

These results allow giving some first conclusions. The « focusing » effect observed at 1 GHz is greatly attenuated at 2.4 GHz and 5.8 GHz. The number of facets and the size of the facets have an important effect on the signal level. It has to be noticed that these conclusions concern large dimensions of tunnel such as TGV tunnels where GSM-R is deployed. We will then consider smaller dimensions of tunnels corresponding to mass transit tunnels.

4.2. Tunnel dimensions influence

Tunnel with small cross section like mass transit tunnels are considered in this part. The tunnel A represents a square cross-section tunnel with a size of 4.5 m, the tunnel B is an arched cross-section tunnel modeled by 3 facets, and the tunnel C is an arched cross-section tunnel modeled by *n* facets.

Simulations are performed at 1 GHz, 2.4 GHz and 5.8 GHz. The transmitting and receiving antennas are dipoles vertically polarized and placed respectively in (2.25, 0, 3.5) and (1, y, 1.5), y varying from 10 to 150 m with a step of 1 m. High frequency conditions imply

at 1 GHz :

$$4 \le n \le 11 \tag{4}$$

at 2.4 GHz :

$$4 \le n \le 28 \tag{5}$$

at 5.8 GHz :

$$4 \le n \le 68 \tag{6}$$

Figures 4.6, 4.8 and 4.10 illustrate results obtained for tunnel C at the 3 frequencies function of the size of facets. Figures 4.7, 4.9 and 4.11 show the results for tunnels A, B and C (considering a size of facets giving the higher signal level) to illustrate the effect of section geometry.

Similar conclusions than previous ones can be given in the case of small tunnels. An important variation is observed on the signal level for different size of facets. A « focusing » effect for the arched section is also highlighted compared to the rectangular one.

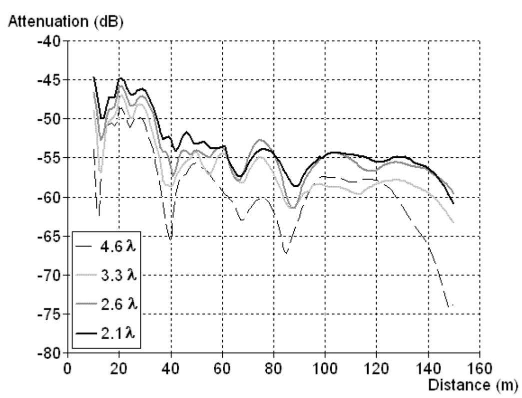

Figure 4.6 : Results for Tunnel C function of facets size 1 GHz

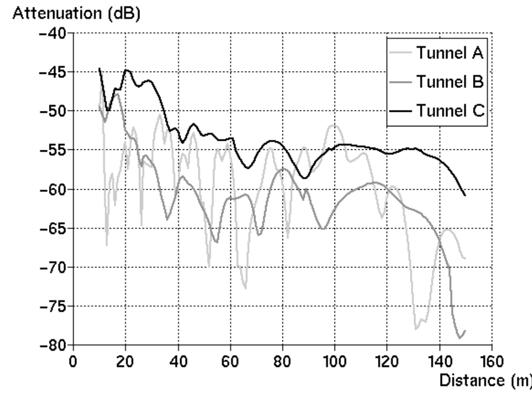

Figure 4.7 : Results for Tunnels A, B, C (facets size = 2.2λ) - 1 GHz

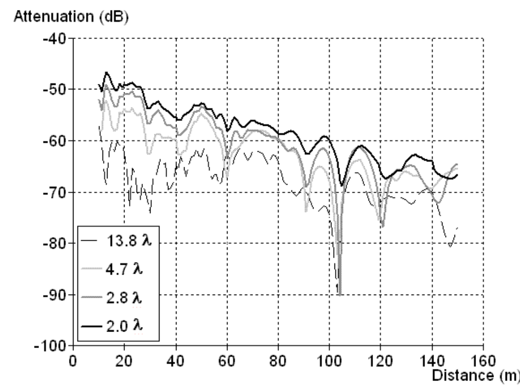

Figure 4.8 : Results for Tunnel C function of facets size 2.4 GHz

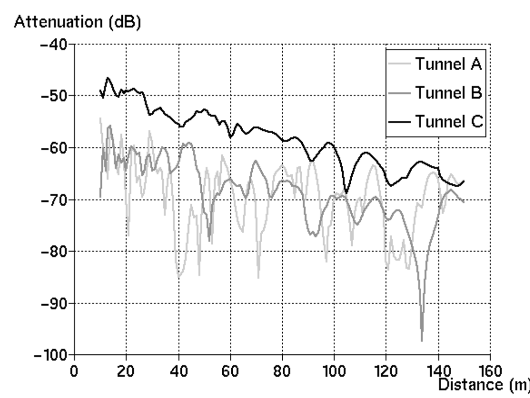

Figure 4.9 : Results for Tunnels A, B, C (facets size = 2λ) - 2.4 GHz

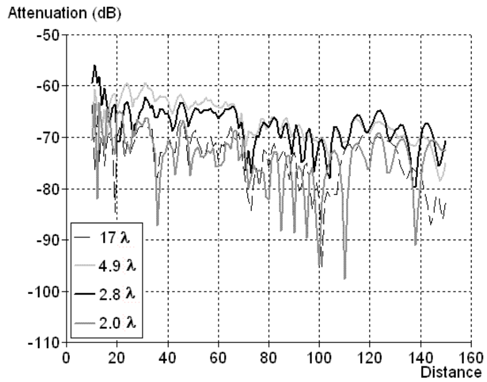

Figure 4.10 : Results for Tunnel C function of facets size 5.8 GHz

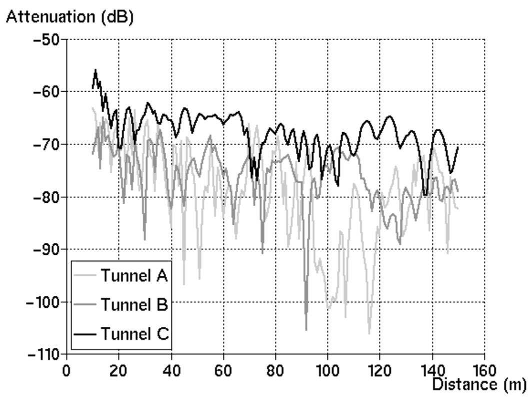

Figure 4.11 : Results for Tunnels A, B, C (facets size = 2.8λ) - 5.8 GHz

5. CONCLUSIONS

This paper illustrates a method to model the radio wave propagation in tunnels. After the presentation of several possible techniques found in the literature, we detailed the results obtained using a Ray-Tracing process combined to a tessellation of an arched cross-section straight tunnel. The influence of some parameters like frequency and tunnel dimensions was analysed.

We realized the study on three configurations of straight tunnels to highlight the influence of shape of tunnels. It allows observing a « focusing » effect for the arched section compared to the rectangular section even if this phenomenon is less marked at higher frequencies. The study was also conducted at three different frequencies : 1 GHz in order to compare the results with the literature ones, and 2.4 GHz and 5.8 GHz, which are the IEEE802.11x standard frequencies. Two dimensions of tunnels were considered : a large tunnel (type TGV) and a small tunnel (type mass transit). All these configurations allowed evaluating the radio wave propagation in tunnels in different conditions. An important variation of signal level can be observed for different number of facets considered. A compromise has to be found on the number of facets. It has to be sufficient to represent the geometry of the arched section but not too large to stay in the limit of validity of the physical model based on a high frequency approach.

These first implementations allowed obtaining first results on the tessellation of curvature. However, we do not know if the size of facets giving the higher signal level corresponds to the real signal level. It represents the perspectives of the work. Some comparisons with measurements in real conditions will be realized. It will be envisaged also to compare with exact methods like FDTD on small sections, for computation time reasons.

6. ACKNOWLEDGMENT

The authors would like to thank the ALSTOM-TIS (Transport Information Solution) who supported this work.

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